

# The Mirya- $\mu$ 1 cosmic ray detector: features and first year observations

Meryem Kübra Dağ<sup>a,b,\*</sup>, Tolga Güver<sup>c,d,e</sup>, Güray Gürkan<sup>h</sup>, Ecem Aktaş<sup>g</sup>,  
Suat Özkorucuklu<sup>f</sup>, Sindulfo Ayuso<sup>i</sup>, Juan José Blanco<sup>i</sup>, Zahide Funda Bostancı<sup>c,d</sup>,  
Beste Begiçarslan<sup>b</sup>, Mustafa Turan Sağlam<sup>b,j</sup>, Ahmet Polatoğlu<sup>k</sup>, Cahit Yeşilyaprak<sup>k,l</sup>

<sup>a</sup> Durham University, Centre for Advanced Instrumentation Department of Physics, Durham DH1 3LE, UK

<sup>b</sup> Istanbul University, Institute of Graduate Studies in Science, Department of Astronomy and Astrophysics, Istanbul 34134, Turkey

<sup>c</sup> Istanbul University, Observatory Research and Application Center, Istanbul 34119, Turkey

<sup>d</sup> Istanbul University, Faculty of Science, Department of Astronomy and Space Sciences, Istanbul 34119, Turkey

<sup>e</sup> Georgia Institute of Technology School of Physics, Georgia Institute of Technology, 837 State St NW, Atlanta 30332, GA, USA

<sup>f</sup> Istanbul University, Faculty of Science, Department of Physics, Istanbul 34134, Turkey

<sup>g</sup> Istanbul University, Institute of Graduate Studies in Science, Department of Physics, Istanbul 34134, Turkey

<sup>h</sup> Istanbul University, Faculty of Science, Department of Physics, Nuclear Physics Division, Istanbul 34134, Turkey

<sup>i</sup> Department of Physics and Mathematics, Space Research Group, Universidad de Alcalá, Ctra. Madrid-Barcelona km 33, 6, Alcalá de Henares 28871, Spain

<sup>j</sup> Erciyes University, Science Faculty, Department of Astronomy and Space Sciences, Kayseri 38030, Turkey

<sup>k</sup> Ataturk University, Science Faculty, Astronomy and Space Sciences Department, Erzurum 25050, Turkey

<sup>l</sup> Türkiye National Observatories, DAG, Erzurum 25050, Turkey

Received 24 March 2025; received in revised form 20 May 2025; accepted 22 May 2025

Available online 27 May 2025

## Abstract

We introduce the Mirya- $\mu$ 1 Cosmic Ray Detector, the largest and only cosmic ray detector in Türkiye designed for space weather research. Mirya- $\mu$ 1, modeled and built after the Muon Impact Tracer and Observer (MITO) (Ayuso et al., 2021), is located at the Eastern Anatolia Observatory (DAG) site of the Türkiye National Observatories in Erzurum, Türkiye, at an altitude of 3099 meters. This elevation positions Mirya- $\mu$ 1 among the highest-altitude cosmic ray detectors globally. The detector consists of two stacked scintillator counters, each measuring  $1 \times 1$  meters, separated by a vertical distance of 1.36 meters. Each scintillator is monitored by four H1411 Hamamatsu photomultiplier tubes, enabling precise detection and measurement of light by incident cosmic rays. In this study, we present the data collected throughout 2024, which includes the detection of two Forbush decrease events in March and May 2024. These significant detections demonstrate the capability of Mirya- $\mu$ 1 to contribute valuable data for space weather research, establishing its potential as a critical instrument for cosmic ray studies in the region. © 2025 The Author(s). Published by Elsevier B.V. on behalf of COSPAR. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

**Keywords:** Cosmic rays; Muon detector; Space weather

## 1. Introduction

Cosmic rays are particles from deep and nearby space that are continuously entering our solar system and interacting with Earth's atmosphere. The energy range of cos-

mic rays varies between  $10^9$  eV and  $10^{21}$  eV, making them one of the highest-energy phenomena in the Universe. Due to their charged nature, they encounter magnetic fields during their journey and deviate from their original trajectories (Stanev, 2010; Matthiae and Verzi, 2015). Cosmic rays with energies above  $10^{15}$  eV are generally thought to be accelerated by high-energy events occurring outside our galaxy, while lower-energy cosmic rays originating from sources within our galaxy. Before reaching Earth,

\* Corresponding author at: Durham University, Centre for Advanced Instrumentation Department of Physics, Durham DH1 3LE, UK.

E-mail address: [meryem.k.dag@durham.ac.uk](mailto:meryem.k.dag@durham.ac.uk) (M.K. Dağ).

these particles are referred to as primary particles. Approximately 90% of the primary particles are protons, 9% are helium nuclei, and 1% consist of electrons and other heavy atomic nuclei. When primary particles collide with heavy atomic nuclei in the upper atmosphere, they decay into secondary particles such as pions ( $\pi^\pm$ ), kaons ( $K^\pm$ ), and muons ( $\mu^\pm$ ) (Grieder, 2001). Muons ( $\mu^-$  and  $\mu^+$ ) can be easily detected by using scintillators and are the most numerous charged particles at sea level.

Cosmic rays have recently gained significant importance in space weather monitoring. During their journey through the heliosphere, cosmic rays are modulated by solar activity, including events such as coronal mass ejections (CMEs) and shock waves (Cane et al., 2000). As a result of this modulation, cosmic rays are considered crucial for space weather studies in several respects. Firstly, cosmic rays possess long mean free paths, which are sufficient to carry precursor signatures of disturbances occurring between the Sun and Earth. Furthermore, their Larmor radii are larger than Earth's magnetosphere but smaller than the radius of typical disturbances in the heliosphere. Consequently, cosmic rays can travel without being influenced by Earth's magnetosphere while still carrying information about solar activity. Prior to geomagnetic events, the isotropy of muon flux is often disturbed, indicating incoming geomagnetic disturbances (Ayuso et al., 2021; Kuwabara et al., 2006).

Forbush decreases (FDs) are transient and sudden reductions in cosmic ray intensity measured on ground-based detectors. This phenomenon is generally associated with the Sun's magnetic activity, including coronal mass ejections (CMEs), magnetic clouds, and interplanetary shock waves (Cane, 2000; Fushishita et al., 2008). It is believed that the intense magnetic fields carried by such solar activity interact with galactic cosmic rays, leading to their scattering or deflection, ultimately causing a reduction in the flux reaching Earth. This makes FDs an important event proposed for space weather monitoring (Cane, 2000; Stanev, 2010). However, while the connection between CMEs and FDs is well documented, the precise mechanisms governing the onset and magnitude of these decreases require further observational and theoretical investigation (Dumbovic et al., 2024; Arunbabu et al., 2013).

The detection of cosmic rays is typically carried out using neutron monitors or muon detectors. The Global Muon Detector Network (GMDN), consisting of muon detectors distributed across the globe, and the Neutron Monitor Database (NMDB), consisting of neutron monitors, play a critical role in sharing data between detectors located in different regions (Rockenbach et al., 2014; Usoskin et al., 1997). These networks enable the observation of how solar activity affects cosmic ray flux globally. Additionally, muon detectors have been shown to provide earlier precursor detections compared to neutron monitors due to their sensitivity to a wider energy range (up to several hundred GeV). Moreover, muon detectors have been

operational for a longer period than neutron monitors, providing more extended datasets for studying long-term trends in anisotropies and other cosmic ray variations as a function of solar cycles (Duldig, 2000b).

We here introduce the Mirya- $\mu$ 1 Cosmic Ray Detector, based on the design of Muon Impact Tracer and Observer (MITO) cosmic ray detector, operated in Antarctica by the University of Alcalá, Spain (Ayuso et al., 2021). Like MITO, Mirya- $\mu$ 1 consists of two scintillators, each with an area of 1 m<sup>2</sup>, and eight PMTs installed at the four sides of each scintillator. MITO was chosen as a reference due to its straightforward design, which requires fewer components and electronics compatible to the other systems. Additionally, MITO can determine particle trajectories by comparing pulse heights in each scintillator, providing both cosmic ray count rates and impact position data (Ayuso et al., 2021).

Mirya- $\mu$ 1 is a key component of Türkiye's first space weather monitoring station. It aims to provide space weather predictions by investigating the relationship between solar activity and cosmic ray intensity/isotropy, such as Forbush decreases. The detector has been operating almost continuously for over a year at the Türkiye National Observatories' Eastern Anatolia Observatory (DAG) site in Erzurum, Türkiye. In Section 2 we introduce the details of Mirya- $\mu$ 1 and its components. In Section 3 we provide information on the observatory site where Mirya- $\mu$ 1 is located. Finally, we show the first year data in Section 5 and conclude in Section 6.

## 2. Instrument design and components

As previously mentioned, the Mirya- $\mu$ 1 detector is built based on the MITO cosmic ray detector (Ayuso et al., 2021). The MITO detector was chosen as a model due to its minimal number of components and feasibility for construction under laboratory conditions. Additionally, this design is suitable and sufficient for establishing a system dedicated to space weather monitoring. Having similar systems around the world can also help overcome intercalibration issues when the same events are observed. Table 1 we give a comparison of Mirya- $\mu$ 1 and MITO in Antarctica and Tenerife.

Mirya- $\mu$ 1 is fundamentally a scintillation detector comprising two EJ200 scintillators, each measuring 1 m  $\times$  1 m (100 cm  $\times$  100 cm  $\times$  5 cm, made of poly-vinyl-toluene with 64% anthracene), and eight H11411 Hamamatsu photomultiplier tubes (PMTs).

Mirya- $\mu$ 1 TOP and Mirya- $\mu$ 1 BOTTOM represent the two identical detection systems of the detector, similar to MITO-top and MITO-bottom. Both systems are **horizontally** stacked in a four-layer rack configuration. The middle two layers of the rack are filled with lead sheets to eliminate low-energy particle signals. The working mechanism of Mirya- $\mu$ 1 is no different from a typical scintillation detector. First, light generated by a charged particle passing

Table 1

Comparison of Mirya- $\mu$ 1 and MITO Cosmic Ray Detectors in Antarctica and Tenerife.

Parameters	Mirya- $\mu$ 1	MITO Antarctica	MITO Tenerife
Altitude (m)	3099	sea level	2364
Average Count Rate (8PMT)	2993	1751	1911
Scintillator Size (m <sup>2</sup> )	1.0	1.0	1.0
Scintillator Separation (m)	1.353	1.365	1.493
Scintillator Model	EJ-200	BC-400	BC-400
PMT Model	H11411	R2154-02	R2154-02
Number of PMTs	8	8	8

through Mirya- $\mu$ 1 TOP exits through the four narrow side faces of the scintillator and is directed to four PMTs via air light guides. If the same particle has sufficient energy, it passes through the lead layer and produces scintillation in Mirya- $\mu$ 1 BOTTOM. Each PMT collects light from the four corners of each scintillator (TOP and BOTTOM) and generates a pulse. The pulses from each PMT output are sent to a C7319 Hamamatsu amplifier, where it is amplified and inverted as required, and then sent to the electronic readout circuit. The electronic circuit was also produced considering the MITO design principles (Ayuso et al., 2021).

The Mirya- $\mu$ 1 detector contains two highly sensitive and fragile scintillators, requiring complete isolation from any light other than scintillation. Therefore, a specially designed mechanical system was established. The two profile racks housing the Mirya- $\mu$ 1 TOP and BOTTOM scintillators were fully covered with black cardboard and high-voltage electrical tape (Dag, 2023). The inner compartment housing the scintillator was completely lined with white plexiglass. White color was used to achieve Lambertian reflection (Koppal, 2020) and thus to reflect scintillation light without loss. The joints where the plexiglass meets the profile were first covered with aluminum tape and then with electrical tape, ensuring that all areas inside were carefully sealed to prevent light ingress. The four corners of the profiles supporting each scintillator system were left open to integrate the PMT and amplifier systems. In these openings, PMT holders, produced in the Istanbul University Observatory Laboratory and designed in the Department of Physics, were placed. The PMT holder designs were fabricated using 3D printers (Dag, 2023).

The square iron profiles containing the two separate systems were also incorporated into a four-layer cast iron shelving system (Fig. 1). The two layers in between the scintillators house lead with total 5.5 and 6.5 cm thicknesses. These are not individual solid lead plates but rather in total 40 layers of lead each having 2 mm thickness. In the MITO design, a 10 cm thick lead layer was reported to provide performance equivalent to the neutron detector used in MITO (Ayuso et al., 2021). According to GEANT4 simulations conducted during the MITO setup phase, this lead layer acts as a filter, blocking the passage of charged particles above 200 MeV for muons, 160 MeV for protons, and

more than 5 GeV for electrons (Ayuso et al., 2021). The Mirya- $\mu$ 1 TOP and Mirya- $\mu$ 1 BOTTOM systems are each wrapped by additional light-proof fabric on the shelves they are placed on (Dag, 2023). We note that a complete simulation of the Mirya- $\mu$ 1 detector response is beyond the scope of this paper and detailed GEANT4 simulations are currently underway. In particular, the GEANT4 simulations previously conducted for the MITO detector which shares an identical design with Mirya- $\mu$ 1 are largely applicable (Ayuso et al., 2021).

Similar to the Ayuso et al. (2021) design, the two layers and 8 PMTs provide a setup, which can be used to test the isotropy of the incoming particles. Additionally, the separation in between the scintillators allows for a constrained solid angle. Following the calculation in Ayuso et al. (2021), we can calculate the solid angle subtended by Mirya- $\mu$ 1 as 1.445 sr, given the total separation of 1353 mm, very similar to MITO. Overall GEANT4 simulations show that the angular resolution reached by the system is  $\pm 3.9^\circ$  in the zenith angle and  $\pm 16.2^\circ$  in the azimuth angle for MITO Ayuso et al. (2021), given the identical configuration Mirya- $\mu$ 1 has a similar angular resolution as well.

Because of this configuration, while operating the events that trigger all of the PMTs are not only going to be the most energetic ones, since they are able to pass through the lead layers, but will also be coming from the zenith of the detector with a solid angle of 1.445 sr. The events that only trigger the upper layer will contain both lower energy particles and particles that may be coming from a wider angle. We note that with such a configuration studies related to the cosmic ray isotropy can also be done with Mirya- $\mu$ 1 in the same way it is done with MITO.

## 2.1. Data acquisition

The electronic readout circuit of Mirya- $\mu$ 1 is entirely based on the MITO design (Ayuso et al., 2021) and was developed in collaboration with the University of Alcalá. It was manufactured at the DEKA PCB factory in Istanbul, Türkiye<sup>1</sup>. All electronic module tests were conducted

<sup>1</sup> <https://www.dekaelectronic.com/en/>

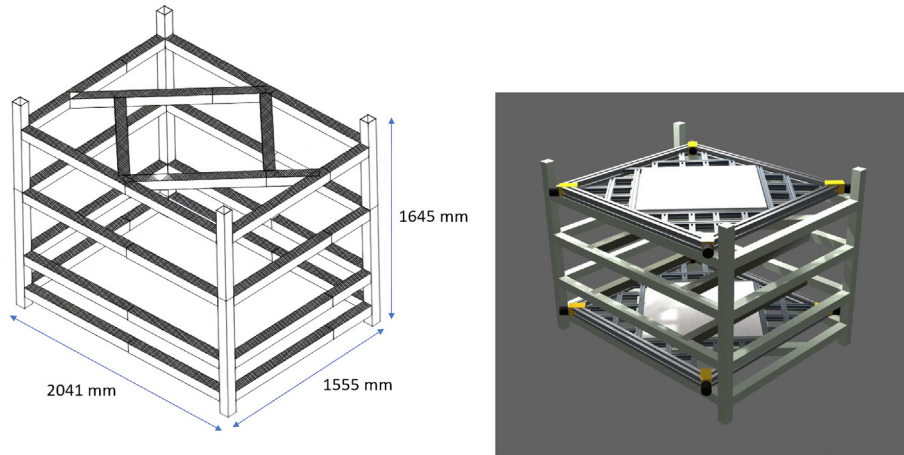


Fig. 1. Isometric view of the four-layer shelves with dimensions labeled. In the left panel only the location of the scintillator on the upper layer is shown. Right panel shows the main detector structure as a 3D model. On the two layers in between the scintillators, we have lead layers, which are not shown for clarity.

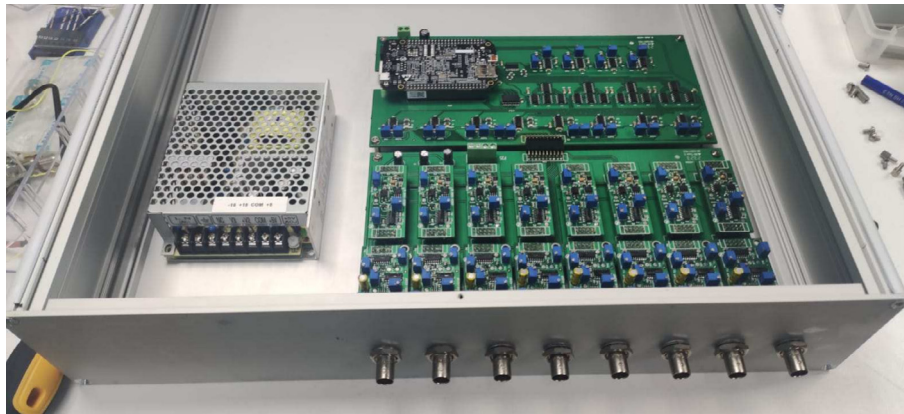


Fig. 2. Mirya- $\mu$ 1 electronic module in a protected box at Istanbul University Physics Laboratory, 2023 (Dağ, 2023).

at the Istanbul University Observatory Laboratory, in coordination with the Physics Department and the MITO team of the University of Alcalá.

The MITO data acquisition system (DAQ) consists of analog and digital processing modules, enabling parallel data analysis. However, Mirya- $\mu$ 1 adopted only the analog module, known as Software-coincidence Acquisition System (SAS), while the digital module, Adaptable and Reconfigurable Acquisition Concept for Nuclear Electronics (ARACNE) (Blanco et al., 2021; Ayuso et al., 2016), was excluded. The analog module (Fig. 2) processes PMT signals by limiting the detectable particle energy range through lower-level (LLD) and upper-level (ULD) discriminators, effectively filtering out noise and high-energy particles (Ayuso et al., 2021).

In Mirya- $\mu$ 1, as in MITO, a Beaglebone Black<sup>2</sup> single-board computer (SBC) manages data processing. The detected pulses from all eight channels are captured, analyzed for overlap and amplitude, and stored for further analysis (Ayuso et al., 2021).

## 2.2. Voltage control

Selected PMT modules have built-in high-voltage (HV) generators and require only +5 V to operate. In addition, the HV level can be adjusted via a control voltage pin. To achieve digital control of PMT HV levels, 8 independent ADC (ADC121C021, Texas Instruments) and DAC (LTC2631, Analog Devices) loops are used. These loops can individually generate 0–1.8 V output voltage range. The ADC read and DAC output assignments are achieved via Arduino Uno board<sup>3</sup> with I2C protocol. I2C addresses of ADC and DAC chips are assigned via jumpers as shown in Fig. 3 and Table 2. For user friendly control, a serial communication-based voltage query and control algorithm is developed.

## 3. Eastern Anatolia observatory

The variation in cosmic ray intensity with altitude has been demonstrated multiple times through studies, con-

<sup>2</sup> <https://docs.beagleboard.org/boards/beaglebone/black/index.html>

<sup>3</sup> <https://www.arduino.cc>



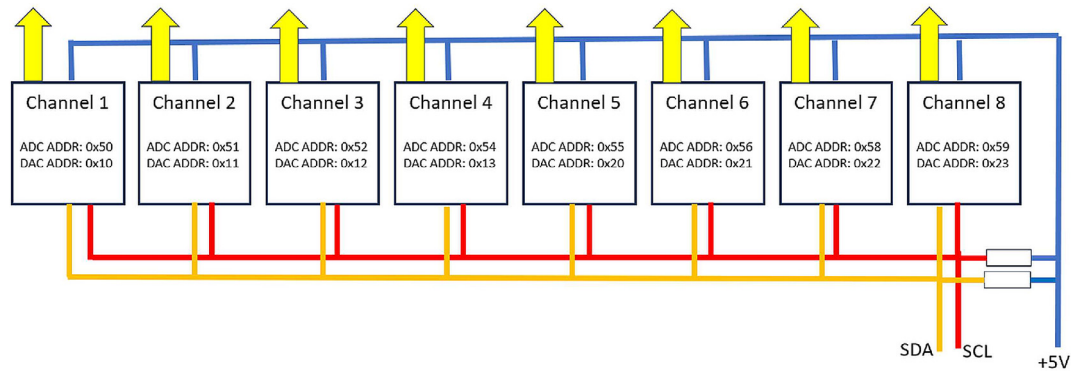


Fig. 3. Block diagram illustrating the I2C-based control architecture for PMT high-voltage adjustment.

Table 2

I2C address assignments for ADC (ADC121C021) and DAC (LTC2631) chips via jumper settings.

	1	2	3	4	5	6	7	8
<b>K4(A0)</b>	FLOATING	FLOATING	GND	+Vcc	FLOATING	GND	FLOATING	GND
<b>K2(A1)</b>	FLOATING	GND	FLOATING	FLOATING	GND	+Vcc	+Vcc	+Vcc
<b>K3(C0)</b>	GND	GND	FLOATING	+Vcc	GND	+Vcc	GND	FLOATING
<b>K1(C1)</b>	GND	GND	GND	FLOATING	FLOATING	+Vcc	+Vcc	+Vcc

tributing to the discovery of cosmic rays (Hess, 1940). The cosmic ray flux at sea level is approximately  $1\text{--}2$  particles  $\text{cm}^{-2} \text{ s}^{-1}$ , and at 3000 meters it increases by a factor of ten, while at 5000 meters it increases by a factor of twenty (Grieder, 2001; Polatoglu et al., 2022). The change in cosmic ray intensity, depending on atmospheric density, makes the location of cosmic ray detectors crucial.

Mirya- $\mu 1$  was initially installed at the Istanbul University Observatory Laboratory, located on the Beyazıt campus, where it was constructed. The coordinates of this location are  $41^{\circ}00'46.93''$  N,  $28^{\circ}57'49.95''$  E, and its altitude is 69 meters. At this altitude, which is quite close to sea level, several initial measurements were conducted over few days. The detector was later relocated to its target site, the Eastern Anatolian Observatory (DAG), where it has been operational since October 19, 2023.

DAG hosts Türkiye's largest and also the first infrared (IR) telescope with a mirror diameter of 4 meters (Keskin et al., 2014). The DAG site is located approximately 35 km from the city center of Erzurum by road, on the Karakaya Hills, which are the western extensions of the Palandöken mountain range. The observatory is positioned at  $39^{\circ}46'43''$  N,  $41^{\circ}13'37''$  E at an altitude of 3170 meters (Yuzlukoglu et al., 2024). The site's high altitude, low humidity, low turbulence, and favorable atmospheric conditions, make it one of the most important locations in the northern hemisphere for astrophysical studies (Balbay et al., 2024).

The Mirya- $\mu 1$  detector is installed approximately 200 meters south of the DAG telescope, in a basaltic geological formation. Although the DAG telescope, due to its slightly higher position, has partial visibility of the city of Erzurum, the location of Mirya- $\mu 1$  does not have a direct line of sight to the city center. The detector is located in an open high-

land plain, surrounded by mountainous terrain, with low atmospheric density and very sparse vegetation. The absence of electromagnetic interference at this site significantly enhances the quality of cosmic ray data collection. Moreover, previous measurements conducted at the DAG site using a portable muon detector have confirmed the site's suitability for cosmic ray research (Polatoğlu et al., 2023).

Mirya- $\mu 1$  is housed in a 20-foot dry container (approximately  $6.06 \text{ m} \times 2.44 \text{ m} \times 2.59 \text{ m}$ ), which is insulated against external environmental conditions to minimize temperature fluctuations and environmental noise effects on the measurements. Despite the fact that outside weather conditions can reach anywhere from  $-27$  to  $+25^{\circ} \text{ C}$  (Yüzlükoglu et al., 2024) the HVAC system inside the container is set to fix the container temperature at  $+15^{\circ} \text{ C}$  and has so far been very successful in that.

The exact coordinates and altitude of the detector are  $39^{\circ}46'43''$  N,  $41^{\circ}13'37''$  E and 3099.501 meters, respectively (see, Fig. 4). The location of Mirya- $\mu 1$  at the DAG site and the satellite image of the observatory are shown in Fig. 5. Based on the IZMIRAN geomagnetic cutoff rigidity calculator<sup>4</sup>, the effective cutoff rigidity at the site is  $\approx 3.024 \text{ GV}$ .

#### 4. Meteorological measurements

Atmospheric conditions are another factor that must be considered in muon detection. Changes in atmospheric pressure determine whether muons decay before reaching the Earth's surface, or at which altitude they decay. This leads to variations in the rate of cosmic rays detected by

<sup>4</sup> <https://tools.izmiran.ru/cutoff/>



Fig. 4. Location of the Eastern Anatolian Observatory site in Erzurum, Türkiye is shown.



Fig. 5. *Left Panel:* Eastern Anatolian Observatory site in Erzurum, Türkiye. *Right Panel:* The container housing the Mirya- $\mu$ 1 detector can be seen facing towards  $129^\circ$  from North towards South East.

muon detectors. Therefore, variations in the number of detected events caused by atmospheric conditions must be corrected (Dorman and Yakhno, 1971; Rigozo, 2014; Mendonça et al., 2019).

To account for the effects of atmospheric conditions on muon detection, a dedicated weather monitoring station manufactured at our observatory is used at the DAG site inside the container. This station, located at an altitude of 3099 meters, is equipped with high-precision sensors such as the BMP180 and HDC1080, which continuously measure atmospheric pressure, temperature, and humidity. These parameters are recorded synchronously with muon detection events, enabling real-time corrections for atmospheric influences on cosmic ray flux. The recorded weather station data are also made available online to support further analysis. The observatory also has a dedicated site meteorology station, WXT535 by Vaisala, and has been monitoring the atmospheric conditions at the site for a long time (Yuzlukoglu et al., 2024). We use the pressure measurement by this observatory site to calibrate ours, which is then used to calibrate the cosmic rays as detailed in SubSection 5.1.

## 5. First year observations

After two weeks of experimental operations in Istanbul, Mirya- $\mu$ 1 has been transferred to its final location at the observatory. Since the 19th of October 2023, it has been operating. We here present the data obtained between January 1st, 2024, up to January 1st, 2025. The raw data obtained when only the PMTs in the upper layer are triggered (relatively lower energy events) and when all the PMTs are triggered (higher energy events) are shown in Fig. 6 together with the pressure measurement throughout the year. The detector is operating without any major issues and real-time data can be accessed from a dedicated web page <sup>5</sup>.

### 5.1. Barometric corrections

As mentioned above we use two instruments for barometric corrections, one is in the container next to the

<sup>5</sup> <http://ist60.istanbul.edu.tr/mirya/>

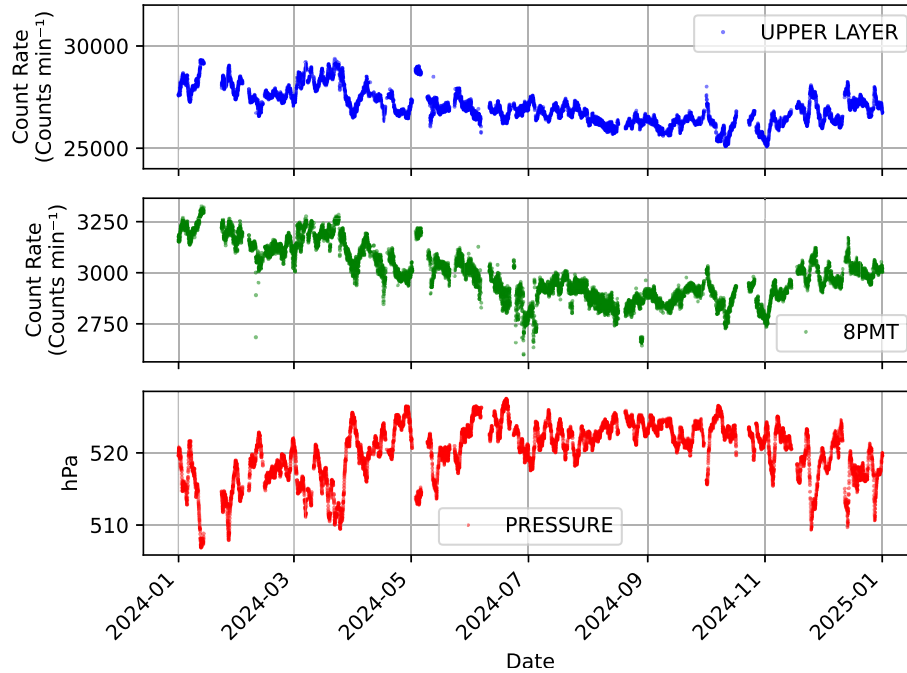


Fig. 6. Event rates from the upper layer (upper panel) when events triggered all the PMTs (middle panel) before pressure correction is applied, and the year long pressure measurements (lower panel). In the plot each point represent the average of sixty measurements obtained every minute.

Mirya- $\mu 1$  and the other one serving for the whole observatory site. Since the barometer in the container worked continuously through the observations presented here, we first calibrated it with the site meteorology station and then used the calibrated inner pressure measurements.

Barometric correction can be applied to cosmic ray data with a relatively simpler approach (Blanco et al., 2023). The correction is empirically performed using the following equation:

$$N = N_0 \exp(-\beta(P - P_0)) \quad (1)$$

In Eq. (1), the  $\beta$  coefficient is expressed as the barometric coefficient. Here,  $N$  represents the corrected count rate,  $N_0$  is the uncorrected count rate,  $P$  is the pressure value, and  $P_0$  is the average pressure value (Blanco et al., 2023). The value of the  $\beta$  coefficient may vary depending on the nature of the measured particle and the altitude of the measurement location (Blanco et al., 2023; Dorman and Yakhno, 1971). This coefficient can be determined by calculating the slope of the count rate dependence to the pressure as shown in Fig. 7. The final pressure corrected data is shown in Fig. 8.

In addition to the effects of atmospheric pressure on the decay altitude of cosmic rays, it has also been shown that atmospheric temperature has significant effects (Duldig, 2000a). However, the temperature effect should be considered primarily in long-term measurements. Seasonal temperature variations cause changes in the thickness of the atmosphere, which may result in the measured cosmic ray rate being higher or lower than its actual value. We also checked if the pressure corrected data shows any temperature related dependence, however no significant long term dependence could be found.

## 5.2. Detected forrush decreases

During its first year of operations Mirya- $\mu 1$  already detected a number of Forbush decreases. Two of these events, which coincided with G4 and G5 geomagnetic storms, occurred in March and May 2024. In the following, we summarize these events and provide the general characteristics of the Forbush decreases detected by Mirya- $\mu 1$ . A full discussion of the observations will be presented in a separate study.

### 5.2.1. March 2024 event

This event involved two active regions (AR 13614 and AR 13615), which produced sympathetic solar flares on March 23, 2024. Among them, an X1.1 class flare occurred from AR3614, peaking at 01:33 UT<sup>6</sup>. A Halo CME with linear velocity of 1470 km/s accompanying the X class flare was detected at 01:25 UT by the LASCO instrument onboard the SOHO.

The CME impacted Earth's magnetosphere, triggering a G4-level geomagnetic storm on 24 March 2024. On the same day, a significant Forbush decrease was observed (Mishev et al., 2024;?). It is reported that this Forbush decrease exhibited unusual characteristics, including a significant reduction in galactic cosmic rays and an exceptionally rapid recovery phase (Mishev et al., 2024).

Mirya- $\mu 1$  also detected a Forbush decrease during this event on March 24, 2024, count rates dropped by 5.98% and 7.16% for the lower-energy and higher-energy events (triggering only the upper layer and all the PMTs, respec-

<sup>6</sup> <https://solarmonitor.org>



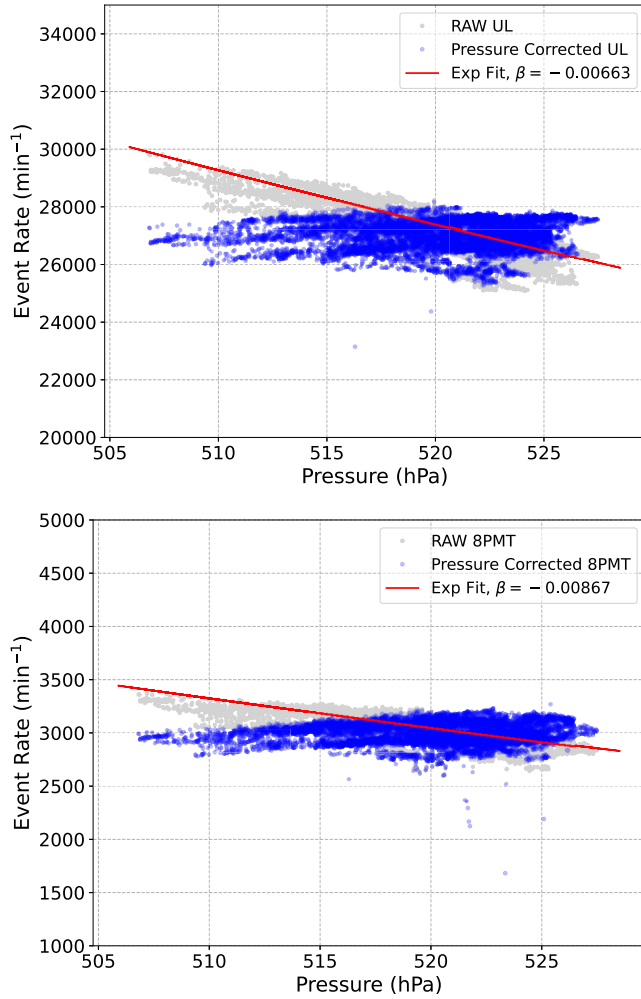


Fig. 7. Comparison of pressure correction effects on event rates for the cases when only PMTs in upper layer (upper panel) are triggered and when all the PMTs are triggered (lower panel). In each plot the grey points represent the raw data, while the blue points show pressure-corrected event rates. The red line indicates the exponential fit with  $\beta = -0.00663$  and  $\beta = -0.00867$ , for upper and lower panel respectively.

tively). It is calculated as the percentage difference between the pre-FD intensity and the minimum intensity observed during the decrease. The recovery time for the 24 March 2024 event was determined to be approximately 1.84 h for the 8PMT and 1.82 h for the Upper Layer data, indicating a rapid return to baseline levels. It was also reported to be 1.5 h at the Oulu neutron monitor station (Mavromichalaki et al., 2024). The Forbush Decrease (FD) recovery time here is determined by first identifying the time of minimum intensity and then finding the moment when the intensity reaches 95% of its average count rate. The recovery time is calculated as shown in Eq. (2):

$$T_{\text{recovery}} = T_{95\%} - T_{\text{min}} \quad (2)$$

### 5.3. May 2024 event

The G5-level geomagnetic storm of May 2024 was the most intense since the 2003 Halloween storm, marking

the strongest event of Solar Cycle 25. This extreme event was triggered by a series of CMEs originating from active region AR 13664, a large and complex sunspot group. This region produced 11 X-class flares, including the largest flare (an X8.7), and at least 10 halo CMEs between May 8 and May 14, 2024 (Hayakawa et al., 2025).

Three CMEs, associated with X-class flares peaking at 04:37 UT and 21:08 UT on May 8, and 08:45 UT on May 9, were identified as the primary contributors to the extreme geomagnetic storm. After propagating for approximately 42 h, these CMEs reached Earth, resulting in a severe geomagnetic disturbance from May 10 to 12, 2024. A significant Forbush decrease was also observed during this period (Chilingarian et al., 2024; Hayakawa et al., 2025; Kwak et al., 2024; Mavromichalaki et al., 2024).

During the event we detected that the count rates dropped by 8.72% and 8.28% for the lower energy and higher energy events (triggering only the upper layer and all the PMTs, respectively). The recovery time for the 10 May 2024 event was determined to be approximately 10.22 h for the 8PMT and 10.04 h for the Upper Layer. Here, the calculation for recovery time was performed using Eq. 2.

## 6. Conclusions

In this paper, we introduced a new muon detector, Mirya- $\mu 1$ , located at the Türkiye National Observatories' Eastern Anatolia Observatory (DAG) site in Erzurum, Türkiye. We present the construction details and components of the detector, emphasizing similarities and differences between Mirya- $\mu 1$  and MITO Ayuso et al. (2021). Having similar detectors in Antarctica and Tenerife may help to compare observations of similar events.

We also present the first year data. The timing of the Mirya- $\mu 1$  detector's installation coincided with the solar maximum phase of the 25th solar cycle (Schwabe, 1844). This alignment is helpful for measuring variations in cosmic ray flux as affected by solar activity since Mirya- $\mu 1$  aims to detect these variations, serving as a precursor to space weather events. On average Mirya- $\mu 1$  detects 27030 events per minute when only the upper layer PMTs are triggered. Most of these events are likely relatively lower energy events. On average, 2993 events trigger all of the PMTs passing through the lead layers, these are the highest energy events Mirya- $\mu 1$  can detect.

A full discussion of all the events within all datasets is out of the scope and will be discussed in a forthcoming paper. However, we note that within its first year of operations Mirya- $\mu 1$  was lucky to be able to witness two very strong geomagnetic storm events resulting in two Forbush decreases observed by cosmic ray detectors from around the world (Mavromichalaki et al., 2024; Mishev et al., 2024; Hayakawa et al., 2025). Mirya- $\mu 1$  detected both of these events and the lightcurves of these two Forbush decreases are shown in Fig. 9. In both cases our measurements are in agreement with earlier observations of Forbush decreases by other muon detectors (Rockenbach et al., 2014; Karapetyan



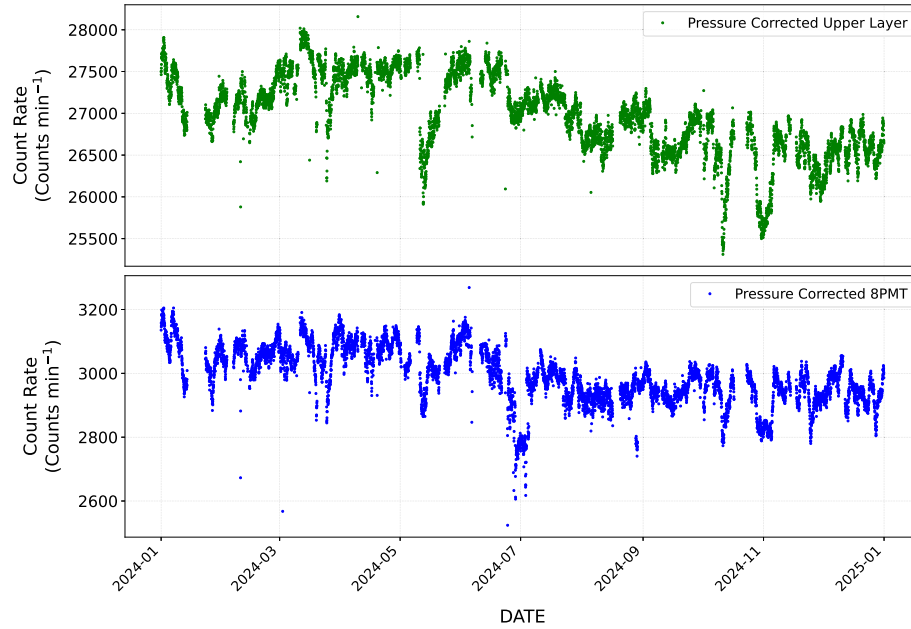


Fig. 8. Number of events detected per minute when only the PMTs at the upper layers are triggered (upper panel) and when all of the PMTs are triggered during 2024 after correction for pressure variations is applied. Each point represent the hourly average of measurements obtained every minute.

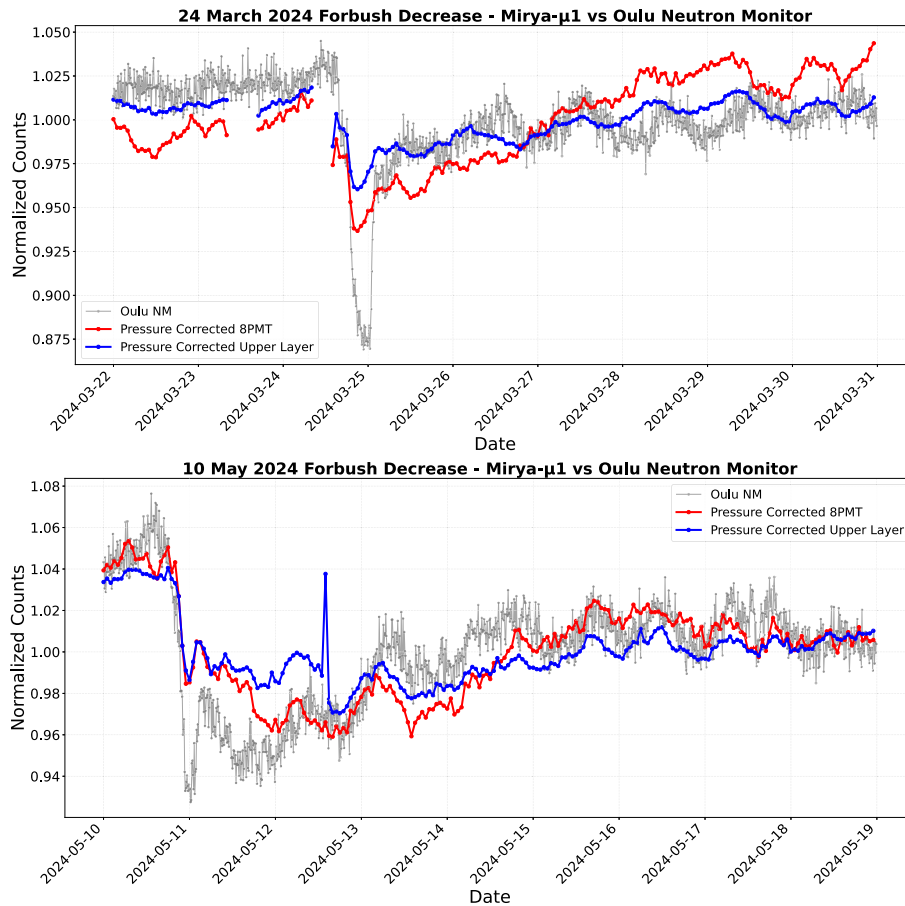


Fig. 9. *Upper Panel*: 24th March 2024 Forbush decrease observed with Mirya- $\mu$ 1 (8PMT and Upper Layer only in red and blue, respectively) and Oulu Neutron Monitor (light grey). The event onset is linked to a high-speed solar wind stream. Unfortunately just hours before the start of the decrease, a power outage on site prevented acquiring data for several hours. *Lower Panel*: 10th of May 2024 Forbush decrease observed with Mirya- $\mu$ 1 (8PMT and Upper Layer only in red and blue, respectively) and Oulu Neutron Monitor (light grey). The sharp decrease on this date corresponds to a CME-induced Forbush Decrease. The sudden increase seen in the upper layer only data is likely thunderstorm related and caused by low energy particles compared to muons. In both panels data is normalized to the mean rate.

et al., 2024; Mishev et al., 2024; Mavromichalaki et al., 2024). A detailed discussion of these events together with comparison of results obtained by MITO and ORCA (Observatorio de Rayos Cósmicos Antártico, Blanco et al. (2023)) will be presented elsewhere but showcases the Mirya- $\mu$ 1's potential to be used for space weather related research in the future.

## 7. Future plans

Given the installation of the Mirya- $\mu$ 1 detector during the solar maximum phase of the 25th cycle, similar events causing variation in cosmic ray flux associated with solar activity are expected to be observed. Moreover, in the long-term operation of the Mirya- $\mu$ 1 detector we plan to be able to cover an entire solar cycle to sensitively observe the anti-correlation between the solar cycle and muon detection rates (Dağ, 2023). The resulting data archive will provide insights into both short-term and long-term modulations of cosmic ray flux due to solar activity.

Finally, we note that construction of a neutron detector has just begun, which will be located at the same site as Mirya- $\mu$ 1 to complement the muon detection measurements. Our plan is to put the neutron monitor on the layers between the two scintillators shown in Fig. 1. This neutron monitor system aims to expand research in this field by measuring cosmic rays of different characteristics and allow for the first time Turkish researchers to obtain their own cosmic ray data for space weather-related studies and contribute to the global network of detectors.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT for translation purposes and for correcting grammatical errors. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

We thank the referees of this manuscript very much whose suggestions and comments improved the text significantly. We appreciate the generous support from Assem-Corp Inc. and especially Mr. AVCI. Without their support, the realization of such a large-scale detector would not have been possible. We thank the Türkiye National Observatories staff for their efforts in keeping Mirya- $\mu$ 1 up and working especially during the harsh winter conditions. T.G. greatly appreciates the hospitality shown at the Georgia Institute of Technology School of

Physics, where part of this work is completed. T.G., M.K.D. has been supported in part by the Royal Society Newton Advanced Fellowship, NAF\R2\180592. T.G., M.K.D., E.A., B.B., M.T.S. S.O., G.G. are supported in part by the Turkish Republic, Directorate of Presidential Strategy and Budget project, 2016K121370. This study was partly funded by the Scientific Research Projects Coordination Unit of Istanbul University Project number FBA-2024-40554. Co-authors Blanco and Ayuso are supported by the project PID2022-140218NB-I00, funded by the Ministry of Science and Innovation. We acknowledge the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract No. 213007) for providing data, and the PIs of the neutron monitors at: Oulu (Sodankyla Geophysical Observatory of the University of Oulu, Finland).

## References

- Arunbabu, K.P., Antia, H.M., Dugad, S.R., Gupta, S.K., Hayashi, Y., Kawakami, S., Mohanty, P.K., Nonaka, T., Oshima, A., Subramanian, P., 2013. High-rigidity forrush decreases: due to cmes or shocks??. *A&A* 555, A139. <https://doi.org/10.1051/0004-6361/201220830>.
- Ayuso, S., Blanco, J., García Tejedor, J., Gómez Herrero, R., Medina, J., López-Comazzi, A., García Población, I., 2016. A coincidence detection system based on real-time software. *Geoscient. Instrument., Methods Data Syst.* 5, 437–449. <https://doi.org/10.5194/gi-5-437-2016>.
- Ayuso, Sindulfo, Blanco, Juan José, García Tejedor, Juan Ignacio, Gómez Herrero, Raúl, Vrublevskyy, Iván, García Población, Óscar, Medina, José, 2021. Mito: a new directional muon telescope. *J. Space Weather Space Clim.* 11, 13. doi:10.1051/swsc/2020079.
- Balbay, R., Kaba, K., Fisek, S., et al., 2024. Evaluation of pwv products derived from satellite-based and radiosonde retrievals for the eastern anatolia observatory (dag). *Exp. Astron.*, 58. doi:10.1007/s10686-024-09949-5.
- Blanco, J.J., García Población, I., García Tejedor, J.I., Ayuso de Gregorio, S., López-Comazzi, A.L., Gómez Herrero, R., Medina, J., Prieto, M. M., Heber, B., Steigies, C.T., Garzón, J., Castro, D.G., Cabanelas, P., Kruger, H., Strauss, D., Blanco, A., Lopes, L., Saraiva, J.P., Gomis Moreno, A., collaboration, O.T., 2021. ORCA (Antarctic Cosmic Ray Observatory): 2018 Latitudinal Survey. In: *Proceedings of Science, Sissa Medialab Srl*. [https://www.researchgate.net/publication/350291592\\_ORCA\\_Antarctic\\_Cosmic\\_Ray\\_Observatory\\_2018\\_Latitudinal\\_Survey](https://www.researchgate.net/publication/350291592_ORCA_Antarctic_Cosmic_Ray_Observatory_2018_Latitudinal_Survey).
- Blanco, J.J., Ayuso de Gregorio, S., García Población, I., García Tejedor, J.I., Gonzalvo Ballano, L., López-Comazzi, A., Regadío, A., Sanz Martín, D., Vrublevskyy, I., 2023. ORCA (Observatorio de Rayos Cósmicos Antártico), current status and future perspectives. In: *EGU General Assembly Conference Abstracts*, pp. EGU–4506. doi:10.5194/egusphere-egu23-4506. (Abstract).
- Cane, H., 2000. Coronal mass ejections and forrush decreases. *Space Sci. Rev.* 93, 55–77. <https://doi.org/10.1023/A:1026532125747>.
- Cane, H.V., Richardson, I.G., St. Cyr, O.C., 2000. Coronal mass ejections, interplanetary ejecta and geomagnetic storms. *Geophys. Res. Lett.* 27, 3591–3594. <https://doi.org/10.1029/2000GL000111>, URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000GL000111>.
- Chilingarian, A., Karapetyan, T., Sargsyan, B., Asatryan, K., Gabaryan, G., 2024. Influence of magnetosphere disturbances on particle fluxes measured by ground-based detectors. *EPL (Europhys. Lett.)* 148, 19001. <https://doi.org/10.1209/0295-5075/ad7e4c>.
- Dağ, M.K., 2023. Mirya-m1 cosmic ray detector; installation, features and first measurements/ Mirya-m1 kozmik isin dedektörü; kurulumu,

- özellikleri ve ilk ölçümler. Master's thesis. Istanbul Üniversitesi/ Fen Bilimleri Enstitüsü/ Astronomi ve Uzay Bilimleri Ana Bilim Dalı/ Astronomi ve Astrofizik Bilim Dalı. Istanbul, Turkey.
- Dorman, L., Yakhno, O., 1971. Determination of barometric corrections to the cosmic ray neutron component intensity variations during solar flares and forrush-decreases using partial barometric coefficient. In: Proceedings of the 12th International Cosmic Ray Conference (ICRC12), p. 932. (Abstract).
- Duldig, M., 2000a. Australian cosmic ray modulation research. Publ. Astron. Soc. Austral. 18. <https://doi.org/10.1071/AS01003>.
- Duldig, M.L., 2000b. Muon observations. Space Sci. Rev. 93, 207–226. <https://doi.org/10.1023/A:1026596529381>.
- Dumbovic, M., Kramaric, L., Benko, I., Heber, B., Vršnak, B., 2024. A new method of measuring forrush decreases. A&A 683, A168. <https://doi.org/10.1051/0004-6361/202346969>.
- Fushishita, A., Kuwabara, T., Kato, C., Yasue, S., Bieber, J.W., Evenson, P., Da Silva, M.R., Dal Lago, A., Schuch, N.J., Tokumaru, M., Duldig, M.L., Humble, J.E., Sabbah, I., Al Jassar, H.K., Sharma, M. M., Munakata, K., 2008. Precursors of the forrush decrease on december 14, 2006 observed with the global muon detector network (gmdn). J. Geophys. Res.: Space Phys. 113, 12–40. <https://doi.org/10.1029/2008JA013233>.
- Grieder, P.K., 2001. Chapter 1 - cosmic ray properties, relations and definitions. In: Grieder, P.K. (Ed.), Cosmic Rays at Earth. Elsevier, Amsterdam, pp. 1–53. doi: 10.1016/B978-044450710-5/50003-8.
- Hayakawa, H., Ebihara, Y., Mishev, A., Koldobskiy, S., Kusano, K., Bechet, S., Yashiro, S., Iwai, K., Shinbori, A., Mursula, K., Miyake, F., Shiota, D., Silveira, M.V.D., Stuart, R., Oliveira, D.M., Akiyama, S., Ohnishi, K., Ledvina, V., Miyoshi, Y., 2025. The solar and geomagnetic storms in 2024 may: A flash data report. Astrophys. J., 979, 49. doi:10.3847/1538-4357/ad9335.
- Hess, V.F., 1940. The discovery of cosmic radiation. Thought: Fordham Univ. Quart. 15, 225–236. <https://doi.org/10.5840/thought1940152136>.
- Karapetyan, T., Chilingarian, A., Hovsepyan, G., Martoyan, H., Sargsyan, B., Langer, R., Chum, J., Nikolova, N., Angelov, H., Haas, D., Knapp, J., Walter, M., Ploc, O., Šlegl, J., Kákona, M., Ambrožová, I., 2024. The forrush decrease observed by the seven particle detector network in the 25th solar activity cycle. J. Atmos. Sol.-Terrest. Phys., 262, 106305. <https://www.sciencedirect.com/science/article/pii/S1364682624001330>, doi: 10.1016/j.jastp.2024.106305.
- Keskin, O., Yesilyaprak, C., Yerli, S.K., Zago, L., Jolissaint, L., 2014. Turkey's next big science project: DAG the 4 meter telescope. In: Stepp, L.M., Gilmozzi, R., Hall, H.J. (Eds.), Ground-based and Airborne Telescopes V, p. 914547. doi:10.1117/12.2067599.
- Koppal, S.J., 2020. Lambertian reflectance. In: Computer Vision, A Reference Guide. <https://api.semanticscholar.org/CorpusID:11390799>.
- Kuwabara, T., Bieber, J.W., Clem, J., Evenson, P., Pyle, R., 2006. Cosmic ray modulation as an indicator of space weather events. J. Geophys. Res. 111, A08108. <https://doi.org/10.1029/2006JA011733>.
- Kwak, Y.S., Kim, J.H., Kim, S., Miyashita, Y., Yang, T., Park, S.H., Lim, E.K., Jung, J., Kam, H., Lee, J., Lee, H., Yoo, J.H., Lee, H., Kwon, R. Y., Seough, J., Nam, U.W., Lee, W.K., Hong, J., Sohn, J., Kwak, J., Kwak, H., Kim, R.S., Kim, Y.H., Cho, K.S., Park, J., Lee, J., Nguyen, H.N.H., Talha, M., 2024. Observational overview of the May 2024 g5-level geomagnetic storm: from solar eruptions to terrestrial consequences. J. Astron. Space Sci. 41, 171–194. <https://doi.org/10.5140/JASS.2024.41.3.171>.
- Matthiae, G., Verzi, V., 2015. The energy spectrum of cosmic rays at very high energy. La Rivista del Nuovo Cimento 38, 73–132. <https://doi.org/10.1393/ncr/i2015-10109-9>.
- Mavromichalaki, H., Papailiou, M.C., Livada, M., Gerontidou, M., Paschalis, P., Stassinakis, A., Abunina, M., Shlyk, N., Abunin, A., Belov, A., Yanke, V., Crosby, N., Dierckxsens, M., Drube, L., 2024. Unusual forrush decreases and geomagnetic storms on 24 march, 2024 and 11 may, 2024. Atmosphere 15. doi:10.3390/atmos15091033.
- Mendonça, R.R.S., Wang, C., Braga, C.R., Echer, E., Dal Lago, A., Costa, J.E.R., Munakata, K., Li, H., Liu, Z., Raulin, J., Kuwabara, T., Kozai, M., Kato, C., Rockenbach, M., Schuch, N.J., Al Jassar, H. K., Sharma, M.M., Tokumaru, M., Duldig, M.L., Humble, J.E., Evenson, P., Sabbah, I., 2019. Analysis of cosmic rays' atmospheric effects and their relationships to cutoff rigidity and zenith angle using global muon detector network data. J. Geophys. Res.: Space Phys. 124, 9791–9813. <https://doi.org/10.1029/2019ja026651>.
- Mishev, A., Larsen, N., Asvestari, E., Sáiz, A., Ann Shea, M., Strauss, D. T., Ruffolo, D., Banglieng, C., Seunarine, S., Duldig, M.L., Gil, A., Blanco, J.J., García-Población, O., Cervino-Solana, P., Adams, James H., J., Usoskin, I., 2024. Anisotropic forrush decrease of 24 march 2024: first look. Adv. Space Res., 74, 4160–4172. doi:10.1016/j.asr.2024.08.027.
- Polatoğlu, A., Yesilyaprak, C., Kaya, M., Shameoni Niaei, M., Er, H., 2023. New the design and measurements of the portable cosmic ray muons detector (crmd) for an observatory. Univ. J. Phys. Appl. 17. <https://doi.org/10.13189/ujpa.2023.170401>.
- Polatoglu, A., Yesilyaprak, C., Shameoni Neaei, M., Kaya, M., 2022. Dogu anadolu gözlemevi'ne (dag) yönelik ilk kozmik isin dedektörünün kurulması ve test ölçümleri (installation and test measurements of the first cosmic ray detector at the eastern anatolia observatory). Turk. J. Astron. Astrophys. 3, 17–21. <https://doi.org/10.55064/tjaa.1131951>.
- Rigozo, N., 2014. Study of the effects of atmospheric pressure in the time series of muon detector using the method of spectral analysis. Int. J. Geosci. 5, 239–246. <https://doi.org/10.4236/ijg.2014.53025>.
- Rockenbach, M., Dal Lago, A., Schuch, N., Munakata, K., Kuwabara, T., Izzo de Oliveira, A., Echer, E., Braga, C., Mendonça, R., Kato, C., Kozai, M., Tokumaru, M., Bieber, J., Evenson, P., Duldig, M., Humble, J., Aljassar, H.K., Sharma, M., Sabbah, I., 2014. Global muon detector network used for space weather applications. Space Sci. Rev. 182, 1–18. <https://doi.org/10.1007/s11214-014-0048-4>.
- Schwabe, S.H., 1844. Solar observations during 25 years. Astron. Nachr. 21, 233–236. <https://doi.org/10.1002/asna.18440211505>.
- Stanev, T., 2010. Cosmic rays in the Galaxy. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 73–90. [https://doi.org/10.1007/978-3-540-85148-6\\_4](https://doi.org/10.1007/978-3-540-85148-6_4).
- Usoskin, I., Kovaltsov, G., Kananen, H., Tanskanen, P., 1997. The world neutron monitor network as a tool for the study of solar neutrons. Ann. Geophys. 15, 375–386. <https://doi.org/10.1007/s00585-997-0375-9>.
- Yuzlukoglu, F., Yesilyaprak, C., Kaba, K., Ikiz, T., Niaei, M.S., 2024. Analysis of long term atmospheric properties for Eastern Anatolia observatory (DAG) site. Exp. Astron. 58, 8. <https://doi.org/10.1007/s10686-024-09952-w>.
- Yüzükoglu, F., Yesilyaprak, C., Kaba, K., Ikiz, T., Niaei, M.S., 2024. Analysis of long term atmospheric properties for eastern anatolia observatory (dag) site. Exp. Astron. 58. doi:10.1007/s10686-024-09952-w.